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Impact of lifetime on US residential building LCA results

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Abstract

Purpose Many life cycle assessment (LCA) studies do not adequately address the actual lifetime of buildings and building products, but rather assume a typical value. The goal of this study was to determine the impact of lifetime on residential building LCA results. Including accurate lifetime data into LCA allows a better understanding of a product's environmental impact that would ultimately enhance the accuracy of LCA results.

Methods This study focuses on refining the US residential building lifetime, as well as lifetime of interior renovation products that are commonly used as interior finishes in homes, to improve LCA results. Residential building lifetime data that presents existing trends in the USA was analyzed as part of the study. Existing product life cycle inventory data were synthesized to form statistical distributions that were used instead of deterministic values. Product elementary flows were used to calculate life cycle impacts of a residential model that was based on median US residential home size. Results were compared to existing residential building LCA literature to determine the impact of using updated, statistical lifetime data. A Monte Carlo analysis was performed for uncertainty analysis. Sensitivity analysis results were used to identify hotspots within the LCA results.

Results and discussion Statistical analysis of US residential building lifetime data indicate that average building lifetime is 61 years and has a linearly increasing trend. Interior renovation energy consumption of the residential model that was developed by using average US conditions was found to have a mean of 220 GJ over the life cycle of the model. Ratio of interior renovation energy consumption to pre-use energy consumption, which includes embodied energy of materials, construction activities, and associated transportation was calculated to have a mean of 34% for regular homes and 22% for low-energy homes. Ratio of interior renovation to life cycle energy consumption of residential buildings was calculated to have a mean of 3.9% for regular homes and 7.6% for low-energy homes.

Conclusions Choosing an arbitrary lifetime for buildings and interior finishes, or excluding interior renovation impacts introduces a noteworthy amount of error into residential building LCA, especially as the relative importance of materials use increases due to growing number of low-energy buildings that have lower-use phase impacts.

Keywords Environmental life cycle assessment · Interior renovation · Lifetime · Monte Carlo analysis · Residential buildings · Uncertainty analysis

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1 Introduction

The built environment is a major contributor to both social and economic development and represents a large portion of

real capital in many countries; but it is also a primary source of environmental impacts. Furthermore, existing building stock requires continuous investments for repair and renovations (Hovde and Moser 2004). Of the 2.5 billion metric tons of nonfuel materials that moved through the economy in 1990, over 70% were used for construction (Fernandez 2006). In 2010, buildings are estimated to account for close to 40% of US primary energy consumption and greenhouse gas emissions (DOE 2009).

The notion that building structures that would last for centuries is the best environmental solution to our problems does not match with our existing building use trends and knowledge of the built environment. Buildings will be replaced with newer designs that are more suited towards the needs of future occupants. This concept should be considered during initial design, construction, and environmental and economic analysis. History of Kingdome in Seattle, WA, USA, illustrates the importance of including anticipated lifetime of structures during decision-making. Being the largest concrete dome of its time, the stadium was built in 1976 for $67 million with a design lifetime of 75 years, extending potentially up to 120 years with scheduled maintenance. However, the stadium was closed for major repair in 1994 after several ceiling tiles fell, and cost $70 million in repair work. The structure was demolished 6 years after repairs only to be replaced with a new stadium that had cost $430 million when completed (Fernandez 2006). Not accounting for actual lifetime of buildings could have significant economic and environmental consequences.

In many cases, building lifetime is governed by factors not directly related to the building design. For residential buildings in the USA, lifetime is more directly related to social acceptability factors rather than durability or structural problems (Winistorfer et al. 2005).

Life cycle assessment (LCA) is a tool that can quantify the environmental impacts of buildings (Optis and Wild 2010). However, many building LCA studies do not adequately address the actual lifetime of residential buildings and building products, but rather assume a typical value, say 50 years (Keoleian et al. 2001; Adalberth 1997a; Thormark 2002; Winther and Hestnes 1999). This study addresses a gap by determining the impact of lifetime on residential building LCA results. Including accurate lifetime information into LCA allows a better understanding of the life cycle impacts, ultimately enhancing the accuracy of LCA studies.

1.1 Functional unit and scope of the study

The goal of this study was to determine the impact of lifetime on residential building LCA results. Including accurate lifetime data into LCA allows a better understanding of a product's environmental impact that would ultimately enhance the accuracy of LCA results. To this end, the impact of interior renovation products over the lifetime of a residential building was quantified. Overall building impacts were considered on a per building basis. Since the analysis is based on lifetime, a clear definition of residential building lifetime was necessary in order to calculate environmental impacts. The functional unit for the study was chosen as the lifetime of an occupied residential building. The ability of a residential building to safely house occupants and satisfy their demands was assumed to be tied to building lifetime as buildings that fail to do so would be replaced with better designs.

The study focuses on refining the US residential building lifetime, as well as lifetime of interior renovation products such as paint and carpet that are commonly used as interior finishes in homes, to improve LCA results. Consumer products such as household electronics or movable products necessary to support various occupant activities were not included in the system boundary.

Lifetime and life cycle inventory data for buildings and building products have been determined by using statistical distributions and were used to quantify the impact of interior renovation. In order to clearly present its importance, interior renovation was compared to other life cycle phases of a residential building. Residential building lifetime presented in this study is a new contribution to literature. Existing data on product life cycle inventories were synthesized to form statistical distributions that were used instead of deterministic values. Product elementary flow data are used to calculate life cycle impacts of a residential model that is based on median US residential home size. Results were compared to existing residential building LCA literature to determine the impact of using updated, statistical lifetime data. A Monte Carlo analysis was performed for uncertainty analysis. Sensitivity analysis results were used to identify hotspots within the LCA results.

1.2 Building use and lifetime

Lifetimes of commercial and residential buildings are significantly different. Although some studies assume a 50-year life span for office buildings (Kofoworola and Gheewala 2008), reported lifetimes vary from 12 to 15 years (Ang and Wyatt 1999) to 20 years (Anderson and Brandt 1999; Guequirre and Kristinsson 1999). Furthermore, department stores undergo extensive interior renovations every 3–5 years for branding and marketing (Anderson and Brandt 1999). Although a quantitative analysis for residential building lifetimes has not been conducted, the general consensus is that residential buildings have longer lifetimes ranging from 50 to 100 years (Keoleian et al. 2001; Adalberth 1997a, b; Anderson and Brandt 1999; Nassen et al. 2007; Lippke et al. 2004; Thormark 2002; Nebel et al. 2006; Borjesson and Gustavsson 2000; Kellenberger and Althaus

2009; Itard and Klunder 2007; Winistorfer et al. 2005; Winther and Hestnes 1999; Mithraratne and Vale 2004; Fay et al. 2000; Scharai-Rad and Welling 2002; Anderson et al. 2002). However, building lifetimes used in LCA studies are often arbitrarily selected as explicitly stated in many studies (Winistorfer et al. 2005; Keoleian et al. 2001; Thormark 2002; Adalberth 1997a, b; Itard and Klunder 2007; Anderson et al. 2002; Anderson and Brandt 1999; Fay et al. 2000; Winther and Hestnes 1999; Kellenberger and Althaus 2009; Borjesson and Gustavsson 2000; Lippke et al. 2004; Palmeri 2010). Furthermore, Palmeri (2010) mentions the lack of a viable method in published literature to estimate residential building lifetime.

1.3 Factors that influence lifetime of building products

Reasons behind replacing interior finishes can be grouped into three categories: failure, dissatisfaction, or change in consumer needs (Cooper 2004). Failure is related to durability of materials and is a category that can be influenced by the manufacturer and designed during the initial design stage. All materials degrade over time as they are used. In addition to normal wear and tear, UV light, humidity, temperature, biological factors, installation, and maintenance procedures are key degradation factors that affect durability of interior building products.

Dissatisfaction is mostly associated with styling changes, fashion trends, or new products being introduced to the market. In this case, consumers are not necessarily motivated by rational cost-benefit considerations, but rather by their desires and perceptions. Occupant needs may change over time even at the same residence, when occupants have children or become elderly for instance.

In practice, the actual lifetimes of various building products are shorter than what they had been designed for (Ashworth 1996; Plat 1999). Products may be replaced prematurely before technical failure occurs. Occupant behavior influenced by societal trends is an important factor that influences the lifetime of products (Guiltinan 2009; van Nunen and Hendriks 2002; Hermans 1999). However, models that captures the effects of consumer behavior on product lifetimes are not widely used to the best of our knowledge. Lifetime estimation methods that can capture consumer behavior are a necessary step towards modeling lifetime (Cooper 2003).

2 Methods

Methods used to gather and process data, together with assumptions made and equations used to calculate results are described in this section. Data sources for residential building lifetime and interior finishes are presented. Multiple data points enabled the use of distributions for variables. Procedure used to fit distributions and uncertainty analysis of results using Monte Carlo method are described. Results were applied to a residential model for interpretation. A description of the residential model is presented together with related assumptions. Data on different life cycle phases of a residential building were also analyzed in order to compare interior renovation impacts to life cycle impacts.

2.1 Data sources

Multiple data sources were used to determine the lifetimes for this study. Data published by the US Census Bureau were used extensively for building related statistics (Census 1997, 1999, 2001, 2003, 2005, 2007, 2009a, b, c; Friedman and Callis 2008). BEES v4.0 (Lippiatt 2008) and the Ecoinvent v2 and ETH-ESU LCI databases incorporated in Simapro v7.1 software (SimaPro) provided the majority of elementary flow data for building products. TRACI 2 v3.01 (Bare et al. 2003) was used for impact assessment of inventory data.

2.1.1 Residential building lifetime

Accurate data on residential building lifetime was vital since building lifetime determines the number of interior renovations. Data on US residential building stock was published by the US Census Bureau under the 2009 American Housing Survey microdata, which had a sample size of over 70,000 residences (Census 2009a). No other governmental or public source provided such a large number of reliable data points on the US housing stock. Survey microdata included data for when a building was built and whether it was demolished since the last survey. The difference between these two values provided the lifetime for that building. A large dataset including over 3,700 data points for building lifetime was gathered from microdata by this approach.

A caveat of using this data source was that the type of building was not recorded for buildings that were coded as demolished. Therefore, average lifetime of different building types could not be calculated directly from this primary source. However, it was possible to reach a conclusion regarding average lifetime of single-family residential buildings based on three supporting analyses.

On a national scale, single-family detached houses and apartments form 63% and 25% of the US building stock, respectively (Census 2009b). The remaining portion being equally divided between single-family attached homes and mobile units. The difference in average building lifetime of single-family detached houses and apartments was investigated. Average age of existing single-family detached houses and apartments including two or more units were calculated to be 42.4 and 44.1 years respectively from the 2009 American Housing Survey microdata (Census 2009a).

Average age of existing buildings is different from building lifetime, since the building needs to be demolished in order to calculate its lifetime. Nevertheless, the difference in mean age of existing buildings between these two categories was found to be of secondary importance compared to the inherent uncertainty of building age.

Existing buildings were separated according to type and year built. The ratio of single-family detached houses to single-family detached houses and apartments varies within a range of 60–80% over the decades but has an almost constant trend at 70%. Therefore, no evidence was found to support that single-family detached houses and apartments have different lifetimes, and so they were assumed to be the same throughout the current study. A study by O'Connor (2004) surveying 227 demolished buildings found that only eight were demolished due to structural reasons, and that buildings were usually demolished due to changing land values and occupant needs. Results of this study support our assumptions since social factors independent of building type were found to determine building lifetime in most cases.

Buildings built prior to 1920, which constitute 7% of the existing US building stock, were presented in a single category in the 2009 American Housing Survey results (Census 2009a). The 2008 New York Housing Survey divides this category into two sections: structures built between 1900 and 1919, and those built pre-1900, with ratios of 75% and 25%, respectively (Friedman and Callis 2008). The same ratios of 75% and 25% were used to further classify pre-1920 buildings on a national basis into two separate categories of 1900–1919 and pre-1900.

The methods described here were used on past surveys as well to observe the trend in residential building lifetime. Survey results dating back to 1997 were published by the US Census Bureau and were used in this study to plot trends in residential building lifetime (Census 1997, 1999, 2001, 2003, 2005, 2007, 2009a).

2.1.2 Products investigated

Interior finish products that are commonly replaced within US residential buildings were investigated in this study. Paint is usually applied in all buildings to some degree, and therefore was included. Multiple flooring alternatives including carpet, hardwood, linoleum, vinyl, and ceramic were also considered.

Data points for lifetime and elementary flows of interior finishes that were used in the study are given in Table 1. In some instances, a range of values was provided for lifetime of products rather than a single value (Gunther and Langowski 1997; Seiders et al. 2007). In these cases, a uniform distribution was assumed for the given range of values. For long-lasting products such as hardwood and ceramic, some sources indicated that the product was expected to last as long as the building, therefore not necessitating any interior renovation (Seiders et al. 2007; Gunther and Langowski 1997). Due to large uncertainty associated with predicting product lifetime for several decades into the future, the lower lifetime limit was selected during analysis, i.e., 75 years when lifetime was given as 75 or more years.

2.2 Uncertainty in variables

Addressing uncertainty plays a key role in interpreting results of life cycle studies. The use of distributions for lifetime and elementary flow data was preferred over using deterministic values since a realistic uncertainty analysis was not possible otherwise. Risk v5.5 was used for uncertainty analysis (Palisade 2009).

The chi-squared test was used to fit distributions. A goodness-of-fit test is an inferential procedure used to determine how well a given set of data fits a chosen distribution (Sullivan 2007). Originally developed by Pearson in 1900, the chi-squared test is the oldest inference procedure that is still used today in its original form (Johnson and Kuby 2003). A Weibull distribution provided the best fit for residential building lifetime and lifetime of most interior finishes. The use of this distribution to model lifetime is common, supported by standards and guidelines (ASTM 2003, 2005; Kececioglu 1991).

Developments in the field of building LCA's have not been matched by accurate emissions data for building products (Bowles and Gow 1995). Existing databases do not sufficiently cover the vast array of products that exist today. Few data points were located for some building products' environmental impact categories due to lack of reliable publications and confidentiality concerns from the manufacturer's perspective. Therefore, triangular or uniform distributions were defined for variables where an adequate number of data points could not be found.

Since variables were defined as distributions, interior renovation impact results were also calculated as distributions having a mean and a confidence interval. Monte Carlo simulation was used to calculate uncertainty in results. Monte Carlo is a statistical method that uses random values from input parameters and presents a distribution for the output parameter (Soratana and Marriott 2010; Woller 1996). The likelihood of potential outcomes can thus be observed from resulting distributions; 20,000 iterations were used for analysis in this study.

2.3 Interpretation of results through a developed residential model

The goal of the study was to determine the impact of lifetime on residential building LCA. Interior renovation impacts over the life cycle of a residential building model were calculated by using the determined distributions for

Table 1 Data points for lifetime and environmental emissions of interior finishes

	Paint	Carpet	Hardwood	Linoleum	Vinyl	Ceramic
Lifetime (years)	3 (New York Housing Maintenance Code), 4 (Lippiatt 2008), 5 (Kelly 2007; Scheuer et al. 2003), 7 (Pullen 2000), 8 (Mithraratne and Vale 2004), 10 (Adalberth 1997a; Keoleian et al. 2001; Hed 1999; Fay et al. 2000)	5 (Gunther and Langowski 1997; Anderson et al. 2002), 8 (Keoleian et al. 2001; Potting and Blok 1995), 8–10 (Seiders et al. 2007), 9 (Petersen and Solberg 2004), 10 (Pullen 2000), 11, 15 (Lippiatt 2008), 12 (Scheuer et al. 2003; Mithraratne and Vale 2004), 17 (Adalberth 1997a)	10 (Nebel et al. 2006), 20 (Anderson et al. 2002; Nebel et al. 2006), 25 (Nebel et al. 2006), 40 (Jonsson 1999, 1997), 45 (Petersen and Solberg 2004; Scharai-Rad and Welling 2002), 50 (Mithraratne and Vale 2004; Nebel et al. 2006; Adalberth 1997a), 50+[a] (Gunther and Langowski 1997), 100+[a] (Seiders et al. 2007)	7–40 (Gunther and Langowski 1997), 15 (Potting and Blok 1995; Petersen and Solberg 2004), 20 (Gorree et al. 2002; Paulsen 2003), 23 (Petersen and Solberg 2004), 25 (Jonsson 1999, 1997; Seiders 2007), 30 (Lippiatt 2008)	7–40 (Gunther and Langowski 1997), 8 (Potting and Blok 1995), 9, 23 (Petersen and Solberg 2004), 17 (Mithraratne and Vale 2004), 18 (Scheuer et al. 2003), 20 (Pullen 2000; Keoleian et al. 2001; Suzuki and Oka 1998; Paulsen 2003; Jonsson 1999, 1997), 40 (Lippiatt 2008), 50 (Seiders et al. 2007)	20 (Anderson et al. 2002; Nicoletti et al. 2002), 30 (Mithraratne and Vale 2004), 50 (Lippiatt 2008), 75 (Scheuer et al. 2003), 75–100 (Seiders et al. 2007)
Energy (MJ/m^2)	3.0, 3.7, 7.2 (Lippiatt 2008), 3.6 (Adalberth 1997a), 6.6, 6.7, 6.8 (SimaPro), 11 (Keoleian et al. 2001)	89, 102, 111, 122, 131, 209, 214, 239, 242, 242, 253, 274, 276, 282, 285, 296, 320 (Lippiatt 2008), 171 (Interface), 183 (BPS)	250 (Gunther and Langowski 1997), 314, 402, 582 (Scharai-Rad and Welling 2002), 530, 530, 550, 920 (Nebel et al. 2006)	57.7 (Jonsson et al. 1997), 130 (Gunther and Langowski 1997), 161 (Paulsen 2003), 276, 305 (Lippiatt 2008)	56 (Jonsson et al. 1997), 130[b] (Scheuer et al. 2003), 165 (Gunther and Langowski 1997), 170 (Paulsen 2003), 245 (Lippiatt 2008)	347 (Lippiatt 2008)
Global warming potential (kg CO_2E/m^2)	0.05, 0.09, 0.18 (Lippiatt 2008), 0.26, 0.27, 0.37, 0.38 (SimaPro)	5, 5, 10, 11, 12, 12, 12, 12, 13, 13, 15, 17 (Lippiatt 2008), 10.6 (Interface), 11.3 (BPS)	4.4, 5.9, 7.1, 12.7 (Nebel et al. 2006), 29 (Gunther and Langowski 1997), 44, 56, 56 (Scharai-Rad and Welling 2002)	1.6 (Jonsson et al. 1997), 2.6 (Potting and Blok 1995), 6, 10 (Lippiatt 2008), 17 (Gunther and Langowski 1997)	4.1 (Jonsson et al. 1997), 9.4 (Potting and Blok 1995), 12 (Gunther 1997), 10 (Lippiatt 2008)	23 (SimaPro), 26 (Lippiatt 2008)
Acidification (g $H+/m^2$)	0.03, 0.04, 0.08 (Lippiatt 2008), 0.06, 0.09, 0.12, 0.15 (SimaPro)	2, 2, 2, 2, 3, 4, 5, 5, 5, 5, 5, 5, 6, 8, 8 (Lippiatt 2008), 2.1 (BPS), 2.5 (Interface)	5200, 5400, 5700, 11300 (Nebel et al. 2006)[c], 5100, 6100, 6600 (Scharai-Rad and Welling 2002)[c]	1.2 (Gunther and Langowski 1997), 5.6, 6 (Lippiatt 2008)	2 (Gunther and Langowski 1997), 6 (Lippiatt 2008),	4.3 (SimaPro), 9.6 (Lippiatt 2008)
Eutrophication (g N/m^2)	0.00 (Lippiatt 2008), 0.03, 0.53, 0.96, 1.29 (SimaPro)	2, 2, 2, 2, 3, 3, 4, 5, 10, 11, 12, 13, 13, 14, 15 (Lippiatt 2008), 10 (Interface), 12 (BPS)	2, 31, 38 (Scharai-Rad and Welling 2002), 35, 35, 38, 81 (Nebel et al. 2006)	18.9, 23.3 (Lippiatt 2008)	0.02 (Jonsson et al. 1997), 1.7 (Lippiatt 2008)	4 (Lippiatt 2008), 8.3 (SimaPro)
Smog (g NO_x/m^2)	0.5, 0.6, 1.0, 1.1 (SimaPro), 16.2, 16.5, 16.9 (Lippiatt 2008)	24, 24, 24, 25, 28, 33, 47, 50, 58, 58, 61, 63, 64, 64, 64, 64 (Lippiatt 2008)	-	119, 125 (Lippiatt 2008)	40 (Lippiatt 2008)	38 (SimaPro), 122 (Lippiatt 2008)

Multiple references after a data point indicate multiple occurrences in different studies

[a] The sign "+" after a number indicates that expected lifetime was more than the given value

[b] Average values were used to convert mass to volume

[c] TRACI characterization factors were used to convert SO_2 into g H+

building lifetime, building product lifetime, and environmental impact of products. A residential model based on median US residential building size was used to calculate life cycle environmental impacts of interior renovation. Existing single-family detached homes have a median size of 167 m^2 based on the 2009 American Housing Survey microdata, which was used to determine the size of the residential model in this study (Census 2009a). The mean single-family detached home size of 206 m^2 for existing residential buildings calculated from the same microdata places more emphasis on larger homes as compared to the distribution of home size and therefore was not preferred.

A four-bedroom, two-bathroom home was assumed for the residential model with the following specifications: ceiling and interior walls were painted, bathroom walls were painted up to half height and the remaining portion covered with ceramic, wall-to-wall carpeting for the home except for kitchen where vinyl covering was assumed. In total, 550 m^2 of painted surface area, 45 m^2 of ceramic, 122 m^2 of carpeting, and 21 m^2 of vinyl were calculated for the residential model. The interior painted surface area was highly dependent on design, or architectural model of the home, and so a uniform distribution of 500–600 m^2 was used during calculations to account for the high level of uncertainty associated with painted surface area. After the described initial configuration, vinyl was replaced with hardwood and linoleum and results recalculated to account for multiple interior finish configurations.

Equation 1 was used to calculate energy use and environmental emissions of interior finishes over the life cycle of a building. The given equation was used to calculate interior renovation impacts and does not include initial construction stage material use. A 5% waste factor was assumed for all floor-covering materials as construction loss from cutting and fitting of products. This value was based on manufacturer recommendations and examples of its use exist in literature (Keoleian et al. 2001). The same type of product as the previous layer was assumed to be used during interior renovation (e.g., carpet replaced with carpet) throughout the lifetime of the building.

$$\left[\frac{\text{building lifetime}(\text{years})}{\text{product lifetime}(\text{years})} - 1\right] \times \frac{\text{product emissions}(\text{kg CO}_2\text{E}/\text{m}^2)}{\text{efficiency}(\text{m}^2/\text{m}^2)} \times \text{application area}(\text{m}^2) \tag{1}$$

The impact of using arbitrary lifetime values for buildings and interior finishes was also investigated. The mean values determined from building product lifetime distributions were selected in this additional analysis. For building lifetime, 50, 80, and 100 years were chosen arbitrarily since such values were observed to be commonly used in published literature.

2.4 Residential building energy consumption over different life cycle phases

Calculating interior renovation impacts of the residential model enables comparisons to be made between different life cycle phases of a residential building. A distinction can also be made between residential buildings built by using regular materials and techniques, and that are designed to consume less energy during their use phase, or low-energy homes. Consuming less energy during use phase, which is the dominating phase for regular homes, increases the relative importance of other life cycle phases including interior renovation.

Pre-use phase, which includes initial materials use, construction, and associated transportation for both activities, has a mean energy consumption of 4.0 GJ/m^2 with a range of 1.7–7.3 GJ/m^2 based on results of multiple case studies on residential buildings (Mithraratne and Vale 2004; Winistorfer et al. 2005; Keoleian et al. 2001; Thormark 2002; Nassen et al. 2007; Lippke et al. 2004; Sharrard et al. 2008). Pre-use energy consumption of low-energy homes was found to have a higher mean of 6.2 GJ/m^2 with a range of 4.3–7.7 GJ/m^2 (Keoleian et al. 2001; Thormark 2002; Winther and Hestnes 1999). A contributing factor for increased energy intensity in low-energy homes is the thicker shell and the high embodied energy associated with insulation products that are applied for weatherization.

Mean energy consumption during the use phase of existing single-family detached homes in the USA is given by the Energy Information Administration to be 0.45 GJ/m^2/year (EIA 2005). A separate category for low-energy buildings was not present in this primary source. Use phase energy consumption of low-energy homes was estimated to be 0.18 GJ/m^2/year with a range of 0.07–0.41 GJ/m^2/year from published case studies (Keoleian et al. 2001; Winther and Hestnes 1999; Thormark 2002).

Demolition energy and transportation of waste was found to be 0.1–1% of life cycle energy regardless of building type and so was neglected during calculations (Keoleian et al. 2001; Winistorfer et al. 2005; Scheuer et al. 2003; Ortiz et al. 2009).

Total energy consumption over the life cycle of the residential model can then be modeled by using Eq. 2.

$$\left[\text{pre} - \text{use}\left(\text{GJ}/\text{m}^2\right) \times \text{area}\left(\text{m}^2\right)\right] + \left[\text{use}\left(\text{GJ}/\text{m}^2/\text{year}\right) \times \text{area}\left(\text{m}^2\right) \times \text{building lifetime}(\text{years})\right] \tag{2}$$

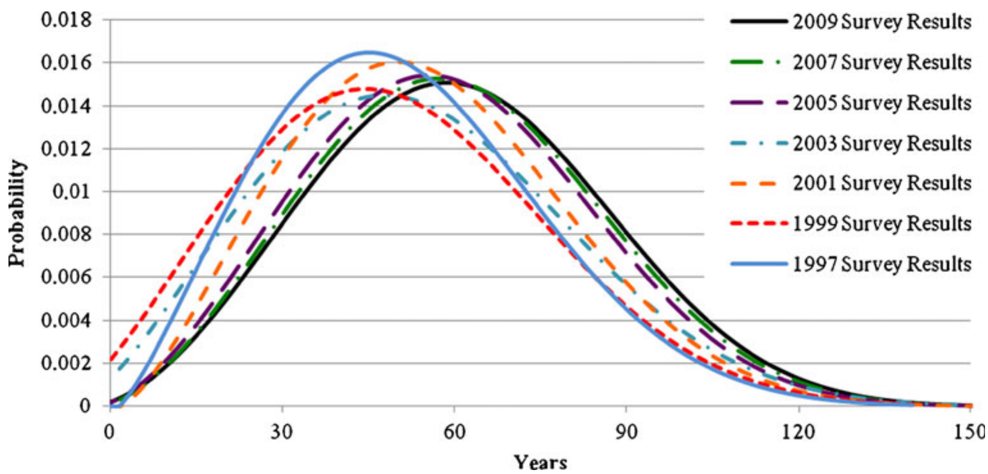

Fig. 1 Lifetime distribution of residential buildings calculated from multiple American Housing Survey microdata

2.5 Sensitivity analysis and validation

Energy consumption and environmental emissions of products over the residential buildings life cycle are a function of multiple variables including multiple products. After a Monte Carlo simulation was performed for an environmental impact category, a sensitivity analysis was conducted to identify variables that contributed most to interior renovation impacts of the residential model.

Paint and flooring alternatives were assumed not to influence residential building lifetime and were also assumed not to affect renovation cycles of other products included in the analysis. This enabled the use of independent variables in the sensitivity analysis.

Findings of this study were applied to published case studies to compare results. A journal article on residential building LCA that is frequently cited by other researchers was chosen to validate results. The applicability of research findings and the level of detail that was presented in the article were also considered during selection.

3 Results and discussion

3.1 Residential building lifetime

Average residential building lifetime was calculated to be 61 years with a standard deviation of 25 years based on the 2009 American Housing Survey. Lifetime is expected to be within a large range of 21–105 years with 90% confidence. Weibull distribution with a shape parameter of 2.8 and a scale parameter of 73.5 provided the best fit to model lifetime of residential buildings. By using the same method, residential building lifetime was also calculated from previous surveys. Figure 1 presents lifetime distribution results for housing surveys conducted from 1997 to 2009.

3.2 Product lifetimes and elementary flow data

Table 2 presents the mean and coefficient of variation values for lifetime, energy consumption, and environmental emissions

Table 2 Mean values, coefficient of variation, and the type of distribution for each variable that is used in this study

	Paint	Carpet	Hardwood	Linoleum	Vinyl	Ceramic
Lifetime (years)	6.9 (0.39, w)	10 (0.32, w)	42 (0.52, w)	22 (0.19, w)	22 (0.45, w)	48 (0.45, t)
Energy (MJ/m^2)	6.8 (0.41, t)	220 (0.31, t)	570 (0.44, u)	200 (0.40, t)	160 (0.41, t)	350 (0.08, u)
Global Warming Potential (kg CO_2E/m^2)	0.2 (0.32, t)	11 (0.28, t)	38 (0.33, t)	10 (0.58, u)	9.3 (0.31, t)	25 (0.12, u)
Acidification (g H+/m^2)	0.1 (0.41, t)	5.0 (0.33, t)	6,300 (0.23, t)	4.5 (0.41, t)	4.0 (0.41, t)	7.0 (0.25, u)
Eutrophication (g N/m^2)	0.8 (0.58, u)	8.5 (0.50, u)	62 (0.52, t)	21.0 (0.14, u)	1.0 (0.58, u)	6.0 (0.58, u)
Smog (g NO_x/m^2)	17 (0.02, u)	50 (0.23, t)	–	120 (0.05, u)	40 (0.14, u)	80 (0.58, u)

Numbers in parentheses represent the coefficient of variation for that distribution. Letters that follow denote the type of distribution used, where, *w* Weibull, *u* uniform, *t* triangular

Table 3 Environmental impacts of interior renovation for the residential model

	Min	Mean	Max	Coefficient of variation
Energy (GJ)	38	220	500	0.64
Global warming potential (t CO_2E)	1.9	11	24	0.63
Acidification (kg H+)	0.8	4.6	11	0.67
Eutrophication (kg N)	1.7	10	24	0.71
Smog (kg NO_x)	28	130	270	0.57

Minimum and maximum values represent boundaries for a 90% confidence interval

data for each product. The coefficient of variation is defined as the ratio of the standard deviation of a distribution to its mean and is a measure of dispersion in data. Table 2 also presents the type of distribution used for each variable, which were developed as described in Section 2.2.

3.3 Elementary flows of the residential model

Impacts of interior renovation over the life cycle of a residential building were quantified. Table 3 presents the energy consumption and environmental emissions of products that were applied to the residential model. Results from all products used in the residential model are combined for each impact category and presented together with a range of results with a 90% confidence interval and the associated standard deviation for the resulting distribution. The combined results represent interior renovation impacts throughout the lifetime of the residential model.

After the initial configuration, additional scenarios were tested to determine the effect of replacing vinyl with linoleum or hardwood in the residential model. Difference in results was found to be minimal.

3.4 Comparing interior renovation to different life cycle phases of the residential model

Environmental impact results of interior renovation over the life cycle of the residential model were used to compare different life cycle phases of a residential building. Energy consumption of interior renovation compared to pre-use phase energy consumption was calculated to have a mean of 34% for regular homes, and 22% for low-energy homes. Figure 2 shows distribution of results together with ranges for the 90% confidence interval. The ratio of interior renovation energy to life cycle energy of residential buildings was found to have a mean of 3.9% for regular homes and 7.6% for low-energy homes. Figure 3 shows distribution of results together with a 90% confidence interval. The range of values given by the confidence intervals should also be seen as the range of possible values that can be computed by using different lifetimes and elementary flows, thus demonstrating the variability they impose on LCA results.

Impacts of using arbitrary values in life cycle studies were analyzed. Table 4 presents results calculated in this study comparatively with those that have been computed by using deterministic values. The lack of a distribution limits

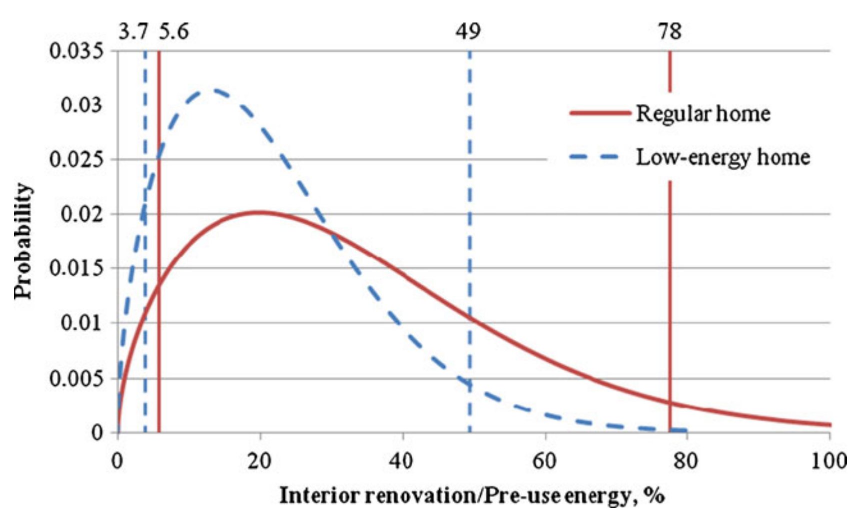

Fig. 2 Distribution for the ratio of interior renovation energy to pre-use phase energy. Given error bars are for a 90% confidence interval

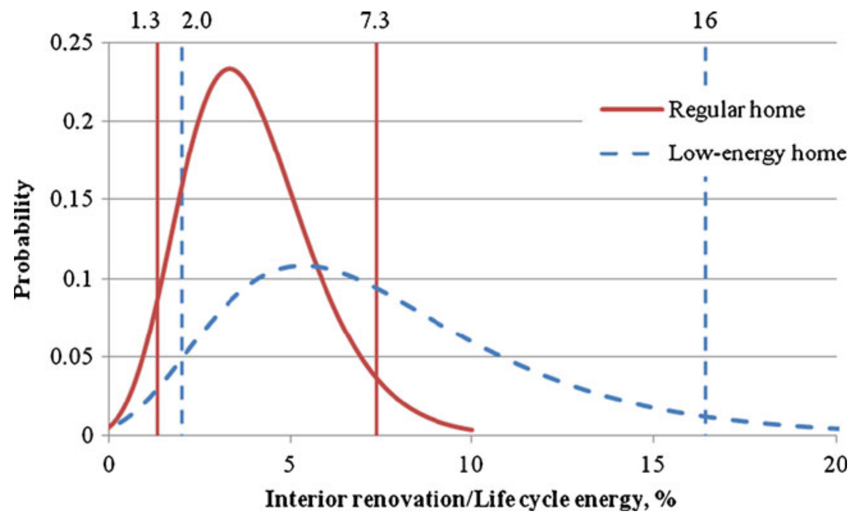

Fig. 3 Distribution for the ratio of interior renovation energy to life cycle energy. Given error bars are for a 90% confidence interval

the ability to provide confidence intervals for results calculated by using deterministic values. Reporting point estimates alone underestimates the amount of uncertainty associated with computed results.

Techniques and materials that improve energy efficiency during the use phase of a building exist today, and are being increasingly applied to new residential constructions. The rapid increase in the number of low-energy buildings signifies public interest towards efficiency and preservation, which will further drive building efficiencies higher. As buildings become more efficient, their use phase elementary flows will decrease, which will increase the relative importance of interior renovation over the life cycle of a building.

3.5 Sensitivity analysis

Sensitivity analysis was performed to determine which variables had the greatest impact on results from the residential model. Figure 4 presents results for energy consumption analysis. A positive regression coefficient indicates that results are directly proportional with changes in that category, whereas negative values indicate an inverse trend. A higher magnitude for the coefficient implies greater impact of that variable on results.

Results of sensitivity analyses should be used to identify hotspots and ultimately improve accuracy of LCA results. More accurate data should be sought for parameters having the greatest impact to improve accuracy of the study. Lifetime data and energy consumption of several interior renovation products were found to equally affect results for the residential model. Therefore, assuming an arbitrary lifetime for products would decrease accuracy as much as choosing a generic emissions factor for building products.

Residential building lifetime was found to have the greatest impact on interior renovation impacts. Following building lifetime, carpeting was found to have the most impact on

Table 4 Impact of choosing arbitrary lifetime values in life cycle studies

		Regular home	Low-energy home
Interior renovation/pre-use energy,%	Results from this study[a]	34 (3.7–49)	22 (5.6–78)
	50 Years building life	22	14.3
	80 Years building life	40	26
	100 Years building life	51	33
Interior renovation/life cycle energy, %	Results from this study[a]	3.9 (1.3–7.3)	7.6 (2.0–16)
	50 Years building life	2.2	4.3
	80 Years building life	4.0	7.8
	100 Years building life	5.1	9.9

Fifty, 80, and 100 years corresponds to arbitrarily chosen building lifetime values. The lifetime of interior finishes has also been taken as deterministic values determined by the mean calculated from their distributions

[a] Values provided for results from this study show the mean value of the resulting distribution and a 90% confidence interval given in parenthesis

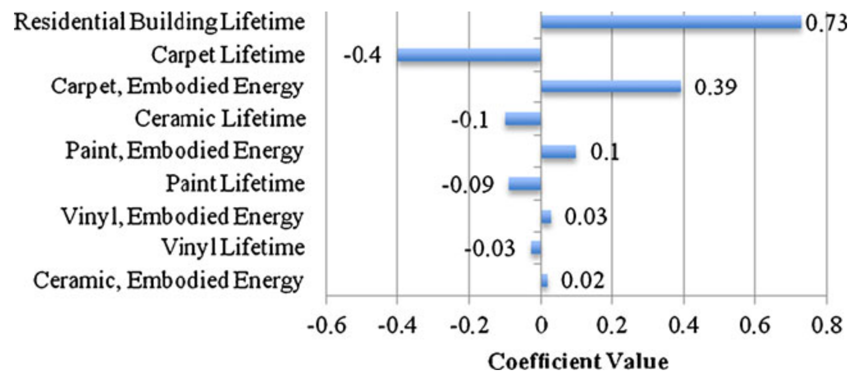

Fig. 4 Sensitivity analysis results for energy consumption of the residential model, ranked based on decreasing influence to results

results. Therefore, a recommendation for future LCA's involving similar materials and conditions would be to focus more on finding accurate data for carpeting compared to other interior finish products.

An additional sensitivity analysis was carried out on distribution selections since different distributions can be selected for a variable. As described in Section 2.2, selections were based on chi-squared test results for the fit between data and proposed distribution. In order to test the impact of distribution selection on end results, distributions different from the ones shown in Table 2 have been chosen, and results recalculated. However, results showed minimal variation in the statistical properties of variables.

3.6 Validation of results

A study by Keoleian et al. (2001) focused on life cycle energy consumption of a 228 m^2 single-family house in the USA. A 50-year residential building lifetime was assumed in the analysis. Renovation impacts have been presented in detail, which allowed results to be directly compared. A description of materials included in the study, together with assumed lifetime and embodied energy data were provided. Renovation cycles were set at 10, 8, and 20 years for paint, carpet, and vinyl, respectively.

Interior renovation impacts have been revised by updating both residential building and building products lifetime. Energy consumption of interior renovation over the residential model lifetime was found to be statistically the same; updated mean value of 370 GJ compared to 320 GJ estimated from figure given in the study. Although there is an increase of 15% in the calculated mean when results are revised for lifetime, the results were within the range of expected results given by the confidence interval. Since similar materials were used in both residential building analyses, the results are in support of each other. Revised energy consumption ratio of selected interior finishes compared to life cycle energy consumption of the model yield 2.3% and 5.8% for regular and low-energy homes, respectively, which are also in accordance with results found in this study.

3.7 Trends in residential building lifetime

Each American Housing Survey contains information regarding the mean age of demolished buildings. The procedure described in Section 2.1.1 was repeated for past surveys. Results given in Fig. 5 show an almost linear increasing trend

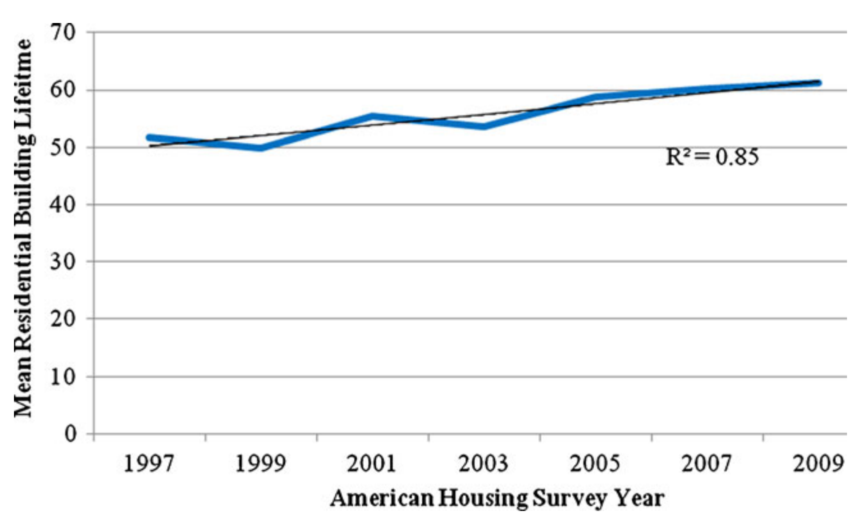

Fig. 5 Change in mean US residential building lifetime (Census 1997, 1999, 2001, 2003, 2005, 2007, 2009a; Nicholson 2009)

in the mean age of demolished residential buildings in the last decade. Values on the *x*-axis denote the year the census survey was carried out and thus the year for which the mean residential building lifetime has been calculated.

However, the observed linear increasing trend cannot continue indefinitely and there is expected to be an upper limit to achievable residential building lifetime dictated by structural design requirements or future technological improvements and demands. A model to predict trends in residential building lifetime is intended to be a future study.

4 Conclusions

Residential building lifetime data that presents existing trends in the USA was analyzed as part of the study. Results indicate that residential building lifetime in the USA is currently 61 years and has a linearly increasing trend. Existing LCA rely heavily on estimates for residential building lifetime and choices are usually made arbitrarily. To our knowledge, this study is the first time mean residential building lifetime has been calculated from a large, reliable sample and used in LCA.

Lifetime of buildings and products presented in the current study should not be taken as static values. Future trends, occupant behavior, population demographics, regulatory policies, or development of new technologies have the potential to alter both lifetime and environmental impacts of buildings and building products. The increasing trend in residential building lifetime was demonstrated in the current study. Range of values supported by statistical analysis was used throughout the study to compensate for some of the uncertainties associated with variables. The use of distributions instead of deterministic values for lifetime of products and buildings improves accuracy of the study and makes results more objective. More data on life cycle inventory data for interior finishes is also a necessary step towards more robust results.

Interior renovation energy consumption for the residential model that was developed by using average US conditions was found to have a mean of 220 GJ over the life cycle of the model. Using published data on energy consumption during pre-use and use phase of residential buildings enabled comparisons to be made among interior renovation impacts and other life cycle phases. Ratio of interior renovation to pre-use energy consumption was calculated to have a mean of 34% for regular homes and 22% for low-energy homes. Ratio of interior renovation to life cycle energy consumption of residential buildings was calculated to have a mean of 3.9% for regular homes and 7.6% for low-energy homes.

Life cycle impacts of traditional buildings are dominated by elementary flows in their use phase. However, this is likely to change as buildings become more energy efficient during their use phase. If the rapid increase in the number of low-energy buildings observed in the last decade continues into the future, use phase impacts of a building would decrease, increasing the relative importance of interior renovation in the life cycle of a residential building. Such an increase would necessitate more focus on interior finishes in a building LCA, since their neglect would result in a greater amount of error.

Due to its influence on product lifetime and related environmental impacts, the effects of consumer behavior related to interior finishes needs to be better quantified in order to improve accuracy of residential building LCA. Since lifetime information plays an important role in life cycle studies, and since consumer behavior can greatly influence product lifetime, is it possible to develop models that can accurately predict product lifetime by including both technical factors as well as consumer behavior? Such a tool would not only improve the accuracy of building LCA studies, but also of product comparison studies as well.

Without fully understanding and quantifying the underlying problems, it is not possible to develop effective environmental impact reducing strategies for the built environment. While collecting data for product lifetime, it was noticed that a product's actual lifetime was usually different than what the product was designed for, and was determined by consumer behavior. Therefore, studying the supply chain from the initial design phase down to individual consumer preferences could open new opportunities to reduce the environmental footprint of products and still maintain economy.

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